MAGNETIC OPENING SWITCH SHAPING THE PRESSURE PULSE FOR HIGH-SPEED LINER IMPLOSION BY HIGH-CURRENT EXPLOSIVE GENERATOR

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Abstract

The paper will present the results of the experiment in which the liner implosion was realized by a pressure pulse shaped by a magnetic opening switch. The current of the high-current explosive generator flows through the ring element of the magnetic opening switch during the time of 430 µs till it rises to 10 MA. The diameter of the copper ring element was 100 mm, length along the axis was 15 mm, and its thickness was 1.2 mm. The ring element was connected to the current-conducting electrodes by the bridges only 0.2 mm thick. Under the effect of magnetic pressure from the flowing ultra-high current the ring element expands in the radial direction. Thin bridges 0.2 mm thick are easily cut in the beginning of the element expansion, and then the ring element is only in sliding contact with the electrodes. Having run the distance of 14 mm, the ring element slides off the current-conducting electrodes. Separation of the ring element happened 30 µs prior to the explosive high-current generator operation completion and prior to reaching the maximum current in it. At the moment of separation the rate of the ring element radial expansion was 1,5 mm/µs. A volumetric arc appears in the gap between the ring element and the current-conducting electrodes. Under the effect of magnetic pressure of ~ 10^9 Pa the magnetized plasma spreads into a toroidal cavity of the coaxial above the imploding cylindrical liner.

The peak current in the high-current explosive generator was 19 MA. The amplitude of current in the toroidal cavity of the coaxial above the imploding liner generated after the separation of the opening magnetic switch' ring element from the electrodes was 18 MA, the time of current rise from 4 MA to 18 MA in the coaxial above the liner was 8 µs. The aluminum liner initial diameter was 100 mm, the wall thickness was 1 mm. The radial rate of the liner implosion was 6.2 km/s.

The analysis demonstrates that the liner acceleration was provided by a combined action of gaskinetic and magnetic pressure of magnetized plasma.

The advantage of the magnetic opening switch is its design simplicity, and also the fact that the pressure pulse shaping is not accompanied by the high-current generator current interruption but is realized by a continuous travel of the conducting medium towards the liner. This increases the efficiency of energy usage for liner implosion. The disadvantage is that as the liner radius decreases the pressure in it increases less than in case of direct current transfer to the liner.

In the experiment considered the toroidal cavity of the coaxial above the liner was not vacuumized. The liner implosion rate may be higher in case the cavity is vacuumized and in case the ring element slide-off moment in the magnetic opening switch is delayed towards the moment of peak current in the high-current generator.

1. Introduction

High-speed liner implosion is one of the main techniques to achieve the substance conditions with high energy densities, pressure and temperature. LANL and VNIIEF have explored the implosion of solid cylindrical liners with a velocity up to 12 km/s at the current amplitude higher than 30 MA. The ultra-high current in the experiments was provided by a disk explosive magnetic generator /1/ and by means of high-power capacitor facility.

To ensure high speed of liner implosion it is necessary that the pressure rise front was short, corresponding to the time of liner implosion from the given initial radius towards the axis. With that purpose in view in those experiments /1/ the electrically exploded foil opening switch, switching the current to the liner load at a 3-4 µs rise front, was used together with DEMG.

This paper will investigate not only a solid liner load but also the magnetic opening switch earlier considered in /2,3/. The known disadvantage of this switch, that is the appearance of some amount of metal vapors when opening the circuit and their transfer to the load region /3/, may turn out to be not really essential in case of a solid liner. A distinctive feature of the presented experiment is that it was conducted under condition of atmospheric pressure in the switch cavity and the load.

II. Experimental assembly.

The experimental assembly is shown in Fig.1. The construction diagram of the assembly is shown in Fig.2.

The assembly includes a system of energy accumulation and generation, and a liner load. The energy generation system has three successive steps of energy generation. The first step is the capacitor facility. The second and third steps are the helical explosive magnetic generator (HEMG) and a four-module high-speed explosive magnetic generator (EMG),and their current and energy gain principle is based on a

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compression of the inductive circuit with magnetic flux by the products of explosive (HE) detonation.

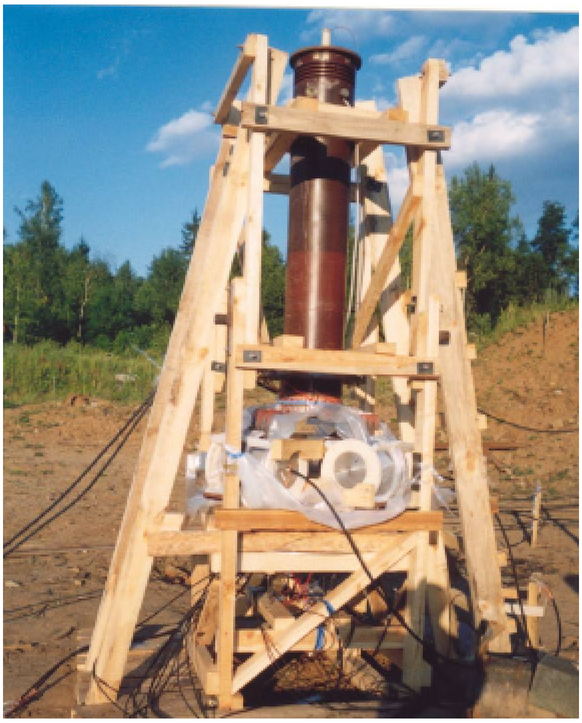

Figure 1. Assembly general view.

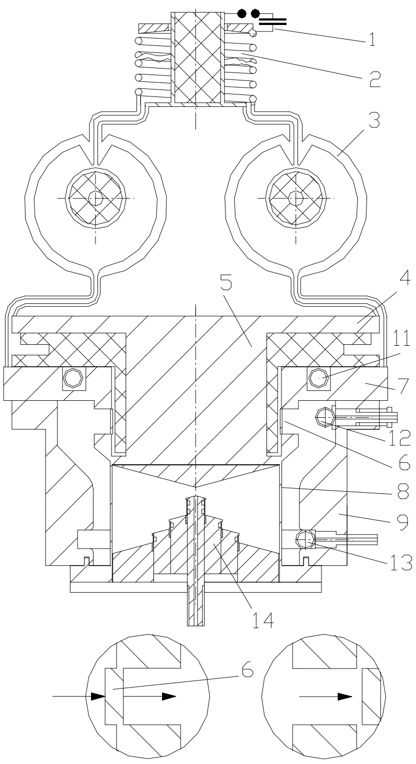

Figure 2. Scheme of experimental assembly and probes layout in the liner load

The diameter of the current circuit of a high-speed EMG is equal to 300 mm, the width of the current circuit is 360 mm. The diameter of HE in the module's inner tube, expanded by explosion, is 152 mm.

The operation of the explosive magnetic system of energy generation was described in/4/.

The liner load contains two current circuits. From EMG the current flows first through the primary accumulating circuit of the load consisting of the input current collector 4, load' central conductor 5 of 90 mm in diameter, movable ring element 6 of the magnetic opening switch, and the output current collector 7. A movable ring element 6 is an outer conductor of the primary circuit. The ring element diameter is 100 mm, height is 14 mm and the wall thickness is 1,1 mm. Under the effect of magnetic pressure the ring element expands outwards in a radial direction from the axis. Due to a step on the inner surface of the conductor the thickness of bridges, connecting the movable ring element with the conductor part of bigger thickness, was decreased to 0,4 mm. In the beginning of the ring element motion the thin bridges are easily cut off and the ring element has a sliding contact with the edge parts of the outer conductor of the EMG load circuit. Having passed 12 mm, the ring element separates from the edge parts of the conductor and an annular slot is formed in the primary accumulating circuit.

The secondary circuit of the EMG load includes a cylindrical liner 9 which is paralleled to a movable ring element of the magnetic opening switch by means of case 10.

It should be mentioned that a secondary circuit of the EMG load does not contain a closing switch. As the resistance of the closed magnetic opening switch is very small, then the current practically should not appear in the secondary circuit prior to separation of the ring element of the magnetic opening switch. The current and pressure on liner 9 should increase effectively only after the separation of the ring element and the appearance of a slot in external conductor 6 of the primary circuit.

III. Experimental results

The probes layout in the load is shown in Fig.2.

B-dot probes are in positions 11, 12, 13 and their signals are proportional to a derivative of magnetic field in these points. The current as a function of time in the primary and secondary circuits was calculated by means of graphical integration of signals from B-dots in the corresponding positions.

To record the displacement of the ring element of the magnetic opening switch and of the cylindrical liner, three types of probes were used. Three fibers with the open ends, spread evenly on the circumference, are directed at the ring element of the magnetic switch on the side of position 12. They record the appearance of electric arc glow occurring at the moment of ring element 6 separation from the current-conducting parts of the primary current circuit.

A displacement of the liner was recorded by the impact-type fiber pins positioned on the steps of the conic insert 15, and by an open fiber directed along the axis. The impact-type fiber pins produced flashes occurring during air compression in the intentionally closed regions made on the steps of the conic insert14.

The flashes were transferred through the fibers from the pins to the high-speed photorecorder.

The plate with edges was inclined so that all the fibers could be in the photorecorder image

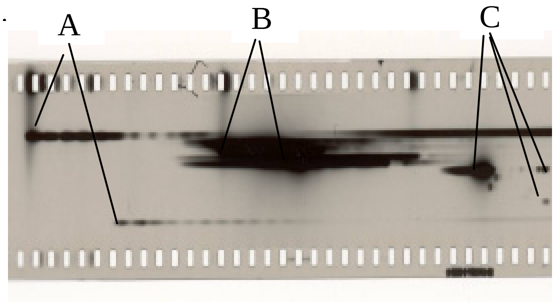

Figura 3. The image of signals from the fiber pins recording the motion of the liner and of the magnetic switch' ring element (taken by a high-speed photorecorder)

The image of the high-speed photorecorder is shown in Fig. 3. The flashes of group A are the reference time markers (460 μs). The flashes of group B are the record of the arc glow occurring at a separation of the ring element. The flashes of group C are the record of air glow on the steps of the conic insert14 and on the liner axis.

The motion of the magnetic switch' ring element and of the liner was additionally recorded by the contact probes having a special scheme generating signals recorded by oscilloscope. Besides that the displacement of the ring element was controlled due to the B-dot probe (position 12) signal leap caused by the ring element impact on the probe.

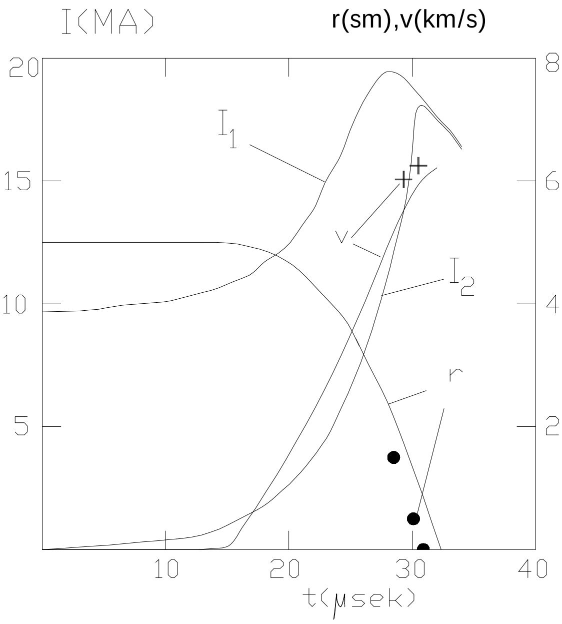

Figure 4. Comparison of current as a function of time in the storage circuit (I_1), current in the liner circuit (I_2), radius (r) and velocity (v) of the imploding liner

Fig. 4 shows the time dependant current in the primary storing circuit of the load before the magnetic opening switch obtained after processing the signal from probe in position 11, and the current in the liner circuit obtained after processing the signal from probe in position 13.

The current value in the primary circuit was 19 MA, the total rise time was 435 μs, the current rise derivative at the final rise section was $1{,}7 \cdot 10^{12}$? /s.

The current in the liner circuit was 18,5 MA, the current rise derivative was $4 \cdot 10^{12}$? /s.

The time moments 494 μs and 495,6 μs of the liner radius reduction to 15 mm and 5 mm taken from the high-speed photorecorder image and the measured moment 496,4 μs of the liner implosion to the axis, as well as the moments 496 μs and 478 μs of the magnetic switch' ring element expansion up to the radii of 62 mm and 72 mm respectively, are given in Fig.5 and are compared with the time dependant current I_1 in the primary storage circuit (pos.11 Fig.2) before the magnetic switch and the current I_2 in the secondary circuit outside the liner (pos.13 Fig.2).

The radial velocity of the ring element expansion was 1.45 km/s. Time moment 496 μs, when the ring element passes the radius of 62 mm, corresponds to a separation of the ring element from the current-carrying sections and formation of a gap in the primary storage circuit.

The gap was formed in the primary circuit at the current of 11 MA in this circuit, 31μs before reaching the maximum current of 19 MA.

To analyze the data on solid liner implosion one should take into account the effect of plasma electric arc occurring in the coaxial cavity of the current circuit of solid liner after the primary storage circuit is broken by the magnetic switch.

In quasi-static approximation the current passage through plasma results in the appearance of gasdynamic pressure gradient.

$\nabla ?_f=\mu_0 \mathbf{j}\cdot\mathbf{H}$ (1)

Taking that **j**=rot **H** and integrating across the length of the coaxial cavity of the liner current circuit one gets the following expression for plasma gasdynamic pressure on the liner.

$$?_f=\frac{m_0}{2}(?_1^2-?_2^2) \qquad (2)$$

where $?_1$ is magnetic field by the magnetic switch, $?_2$ is magnetic field above the liner.

Full pressure on the liner ?Σ was equal to a sum of gasdynamic pressure and magnetic pressure of plasma on liner. Taking into account (2) we get the expression:

$$?\Sigma=\frac{m_0}{2}?_1^2, \qquad (3)$$

which shows that in the taken approximation the full pressure on the liner is equal to magnetic pressure near the magnetic switch.

Expressing $?_1$ through current I_1 in the primary storage circuit, the full pressure on the liner will be written as:

$?\Sigma=\mu_0 I_1^2/8\pi^2 r^2$, (4)

where r is the radius of coaxial cavity of the liner current circuit. It should be mentioned that in the experimental assembly the radius of the ring element in the magnetic switch and the initial radius of the liner were equal and were 50 mm.

The radius and velocity of the solid liner as a function of time, that were calculated with the help of expression (4) using the observed dependence of current I_1, are presented by curves 4 and 5 in Fig.5. Closeness between the experimentally obtained points and the above-mentioned curves confirms that in the experimental assembly the magnitude of pressure formed on the solid liner appeared to be close to the magnitude of magnetic pressure in the primary storage circuit.

IV. Conclusion

A combination of a high-current generator, a magnetic opening switch and a solid liner proves to be effective.

The magnetic opening switch, when closed, has a very low resistance. This allows getting the current amplitude from the high-current generator that is close to the maximum possible amplitude for the applied high-current generator.

The interrelation between the time and current in the storage circuit before the magnetic opening switch and in the solid liner circuit and the data on the liner motion demonstrated that the pressure in the liner current circuit cavity is generated by an integrated action of magnetic pressure and gasdynamic plasma pressure of the arc occurring at the opening of magnetic switch.

Herewith, the magnitude of the integrated action on the liner is close to the magnitude of magnetic pressure in the circuit before the magnetic switch. That's why it is important to form high magnetic fields and current densities on the magnetic opening switch prior to its opening.

Note that the liner velocity could be higher if the moment of magnetic switch opening were shifted closer to the moment of current maximum in the storage circuit of the high-current generator, and the technical vacuum were created in the liner current circuit cavity.

References

[1]A. Buyko, A. Petrukhin, V. Mokhov, V. Chernyshev, B. Anderson, W. Atchison D.Clark, R. Faehl, I. Lindemuth, R. Reinovsky at al., Experimental Simulation of the Energy Parameters of "Atlas" Capacity Bank using a Disk Explosive- magnetic Generator", Digest of Technical Papers 2001 IEEE Pulsed Power Science Conference, ed. by R. Reinovsky, M. Newton, 2001, p. 135.

[2]J. Brownell, R. Bowers, A. Greene, I. Lindemuth at al., "System Requirements for the Los Alamos Foil Implosion Project", Proceeding of the Third International Conference in Megagauss Field Generational and Related Topics", ed. by V.Titov, G. Shvetsov, Moscow, "Nauka",1984, p.221.

[3] A. Petrukhin, V. Mokhov, V. Chernyshev, Proceeding of the Third International Conference in Megagauss Field Generational and Related Topics, ed. by V.Titov, G. Shvetsov, Moscow, "Nauka",1984, p.406.

[4] V.K Chernyshev, V.N.Mokhov, ? .? . Petrukhin, V.A.Vasyukov, V.B.Yakubov, I.R.Lindemuth, R.E.Reinovsky, W.L.Atchison, R.J.Faehl, "Engineering Refinement of the Tern Generator Elements for Liners Model Investigation", "Megagauss-9" Conference, Russia, Moscow – St.Petersburg, 2002, will be published.